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In active quasi-optics, we demonstrated the first successful monolithic HBT and pHEMT millimeter-wave grid amplifiers. In addition, we demonstrated a diode doubler grid with a record output of 24 mW at 1 THz.

We also developed a series of Class-E amplifiers for communications and radar that are based on power MOSFET's with output powers in the frequency range from 7 to 14 MHz of 300 to 500 W, and efficiencies of 90%. We recently extended this work to demonstrate VHF and UHF Class-E amplifiers.

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ACTIVE QUASI-OPTICAL DEVICES

FINAL PROGRESS

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October 6, 1999

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Proposal 33955-EL

California Institute of Technology
Pasadena, California

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Scientific Problem Studied

In this contract, we developed active quasi-optical devices that combine the power of many transistors or diodes to achieve a large output. Millimeter wavelengths are attractive for communications systems because extremely high-data rates can be achieved with modest antennas. They are suitable for terminal guidance radars because millimeter waves penetrate fog and smoke. The problem is that at millimeter wavelengths, the output power provided by solid-state devices is much less than required by communications and radar systems. Quasi-optics allows large-scale combining at the level of 100 or 1,000 devices without the losses that are associated with transmission-line combiners. In this contract, we demonstrated the first monolithic quasi-optical amplifiers, and well as record-setting outputs from a diode doubler grid at 1 THz.

A related goal of this project is to develop Class-E RF amplifiers for HF, VHF and UHF communications and radar transmitters that are simple and extremely efficient. The high efficiency often allows these amplifiers to be run without cooling fans. This project takes advantage of the continuing improvements in RF power MOSFETS.

Results

Monolithic Grid Amplifiers

Jeff Liu demonstrated the first monolithic grid amplifier with gain. He measured 5 dB of gain at 40 GHz. The grid produced an output power of 600 mW. Jeff also developed an approach for analyzing the stability of grids. Early grids showed a tendency to oscillate at about 80% of the frequency where the amplifier was designed to have maximum gain. Jeff's analysis predicted the oscillation frequency. Jeff's theory predicted that a series capacitor in the gate lead could either shift the oscillation frequency, or eliminate the oscillations. His experiments agreed with the theory. This theory is particularly important for monolithic grids, which need to work as designed the first time because of the long time delays in fabrication, and the extremely limited number of process runs. This work is now being extended under the Quasi-Optic Power Combining MURI to W-band with Mark Rodwell's new high-speed HBT's.

Michael DeLisio demonstrated the first successful pHEMT grid amplifier, which was fabricated by Lockheed-Martin laboratories. This amplifier gave a gain of 6.5 dB at 44 GHz. The amplifier could be spot-tuned at any frequency between 44 GHz and 60 GHz, giving a gain of 2.5 dB at 60 GHz. This work has recently been extended under the Quasi-Optic Power Combining MURI to a grid with an output power of 5 W at 35 GHz.

Michael DeLisio also demonstrated at 100-element 10-GHz hybrid pHEMT grid at 10 GHz. This work was published in the *Transactions on Microwave Theory and Techniques.* The work was significant in several respects. Previous work in quasi-optical amplifiers had much more limited comparison of theory and experiment. In this paper, the gain was measured for a wide range of frequencies, angles, and polarizer

positions, and there was excellent agreement between theory and experiment. This grid showed a gain of 12 dB at 9 GHz, with a 3-dB bandwidth of 3.7 W and a bandwidth of 15%. The measured noise figure is 3 dB.

THz Doubler grids

Alina Moussessian tested a doubler with 144 Schottky diodes with an output of 24 mW at 1 THz. This greatly exceeds the previous record for a doubler at this frequency, which was 330 μW. These diodes were fabricated by Tom Crowe's group at the University of Virginia, and tested in Jim Allen's group at the University of California at Santa Barbara. The doubling efficiency is quite low, only 0.17%. We plan to investigate whether this can be substantially improved with a dielectric tuning slab.

Class-E Amplifiers

Quasi-optical work in our group is now supported by the ARO Quasi-Optic Power Combining MURI. The final funds in the contract were spent developing high-efficiency power amplifiers. Efficiency is a critical issue in quasi-optical amplifiers, and we believe that it is important to understand the fundamental issues in amplifier efficiency. This is easier to study at lower frequencies, where the voltage waveforms are easily measured.

John Davis worked with a team of undergraduates, Eileen Lau, Kai-Wai Chiu, and Jeff Qin, to develop high-power RF amplifiers. These are Class-E amplifiers that are extremely efficient, with efficiencies in the 90% range at frequencies from 7 to 14 MHz. These amplifiers have output powers between 300 and 500 W, and are based on inexpensive MOSFET's that cost about $10. This work is discussed in the paper that will be published in *QST*. These amplifiers are expected to find application in communications, medical imaging, and in semiconductor processing. We have also done experiments on a 54-W VHF and 1 15-W UHF Class-E MOSFET power amplifiers that show drain efficiencies in the range of 80%. We believe that these amplifiers will have important applications for military communications.

For the 54-W VHF amplifier, the drive power is 5 W. The amplifier features a novel output variable inductor which is a straight piece of the kind of metal tape that is used for coils in very large magnets. It can be tuned by sliding a piece of metal under the strip. This reduces the area underneath the strip, and it makes the inductance smaller. This raise the operating frequency of the amplifier.

For the 15-W UHF amplifier, the drive power is 1.4 W. One problem that we noted with this amplifier is that it was quite difficult to reduce the input VSWR to reasonable levels. Often it was as high as 5. It seemed that the conditions that lead to high efficiency also led to less efficiency. We do not know whether this reflects some fundamental issue in amplification at this frequency, or whether we just need to improve the design, or perhaps add feedback.

Technology Transfer

The monolithic grid amplifier demonstration was the leading edge of a wave of quasi-optical work being sponsored by DARPA Phase 3, monitored by Elliot Brown, and two MURI's on quasi-optical power combining, monitored by James Harvey. Many universities and all the leading manufacturers of millimeter-wave integrated circuits are involved in this program. The quasi-optical tunnel-diode oscillator work has been extended greatly with resonant tunneling diodes (RTD's), in Mark Rodwell's group at the University of California at Santa Barbara, in collaboration with Peter Smith at the Jet Propulsion Laboratory, with an output power of 28 μW at 350 GHz. Chiao's beam-steering idea has evolved into a collaborative effort with the Rockwell Science Center, who does the fabricaiton, and has since received funding from the Naval Surface Warfare Center, and is monitored by James Harvey of ARO.

Industry and Government Interactions

Michael DeLisio's monolithic millimeter-wave HEMT grid was fabricated by Lockheed-Martin Laboratories.

Polly Preventza's transistors for her 43-GHz oscillator grids were fabricated by Mehran Matloubian at Hughes Research Laboratories.

Jeff Liu's monolithic HBT grid was fabricated by Emilio Sovero at the Rockwell Science Center.

David Rutledge attended the NATO Advanced Study Institute in Submillimeter Wave Technology at the Chateau de Bonas, France, along with Charles Church of the Army Research Office. He gave three lectures there that covered active quasi-optics, and Professor Rebeiz' research in millimeter-wave receivers and antennas at the University of Michigan.

As part of John Davis' Class-E amplifier work, we visited the ETO corporation in Colorado Springs, and gave a presentation of our work. ETO is a manufacturer of high-power RF amplifiers.

People

Jung-Chih Chiao worked on a MEMS switch-based millimeter-wave beam steering system. Dr. Chiao received his Ph.D., and went to Bellcore, and then to the University of Hawaii.

John Davis, is the AASERT fellow. John has been developing high-power Class-E amplifiers for the HF frequency range. He will defend his Ph.D. thesis next month, and will go to work for JPL.

Michael DeLisio demonstrated a monolithic pHEMT grid amplifier with gain between 40 GHz and 60 GHz. Michael defended his thesis, and is now an assistant professor at the University of Hawaii.

Jeff Liu completed his work on the first successful monolithic grid amplifier, defended his thesis, and is now working in a wireless group at Rockwell Science Center.

Alina Moussessian completed her Ph.D. on self-complementary grid amplifiers and is now working at the Jet Propulsion Laboratory on planetary radar sounders.

Polly Preventza has been developing hybrid quasi-optical circuits for the 30 to 100-GHz range, complete her Ph.D., and is working at Lehmann Brothers.

Herbert Zirath is a Professor of Electrical Engineering at Chalmers University in Sweden. He was a visitor in our research group during the Spring and Summer of 1998. Dr. Zirath is an expert in the modelling of transistors.

Inventions

None to report.

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